Theodolite and total station measurements of creep rates on San Francisco Bay region faults

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INVESTIGATIONS UNDERTAKEN

During the grant period from October 1, 2003 through September 30, 2004, we have continued to measure aseismic slip (i.e., creep) on San Francisco Bay region faults, extending a project that was begun by Jon Galehouse in 1979. At each measurement site, we determine the amount of strike-slip movement within a width of about 55-280 m across faults to provide long-term observations about creep behavior and unusual or noteworthy fault movement. Monitored faults include the San Andreas, Hayward, Calaveras, Concord-Green Valley, Maacama, Rodgers Creek, and San Gregorio-Seal Cove faults (Figs. 1–7). The surveying is largely conducted by undergraduate Research Assistants under the supervision and training of several long-term project employees and the Principal Investigators.

During the past year we used only a Wild T2002 total station surveying instrument, after experiments convinced us that measurement uncertainties were comparable to those previously obtained using a Wild T3 theodolite. Creep measurements for all sites (Figs. 2–7) were collected using only the T3 between 1979 and 2001, and using only the T2002 since 2002. We have continued to test the usefulness of each measurement site and to identify and establish new sites at important locations. We presently collect regular measurements at 30 localities along alinement arrays on active faults, and have data from additional sites that have had to be abandoned (Table 1). We are continuing to re-measure most sites with a history of creep about once every eight to ten weeks and most sites without any creep history about every three to four months.

In addition to our ten regular sites on the Hayward fault, we annually measure 23 other sites in conjunction with J. Lienkaemper of the USGS. Jon Galehouse began measuring these additional sites in 1994, and our team completed its fourth collaborative set of measurements in October 2004. Detailed information about the fault creep alinement arrays and measurement procedures can be found in Galehouse et al., 1982. The creep data collected between 1979 and 2001 and the creep characteristics at all sites through 2001 are summarized in an Open-File Report (Galehouse, 2002) and an article in the Bulletin of the Seismological Society of America (Galehouse and Lienkaemper, 2003).

RESULTS

San Andreas fault: The three northernmost sites (Point Arena—SA1 to South San Francisco—SA3; Fig. 2A) continue to show no detectable creep, whereas the southernmost site near San Juan Bautista (SA7; Fig. 2B) continues to show an average creep rate of 11.6 mm/yr. A new site at Aromas (SA5; Fig. 2B) that was established to more precisely define the transition between the creeping and non-creeping segments, shows no detectable creep, consistent with previously recorded data at SA6 (Fig. 2B), a nearby site that was destroyed in a major landslide and hence abandoned in 1998. However, we have only a few years of data from SA5, so these results are preliminary. We are carefully monitoring data collected at SA4 in Woodside (Fig. 2A), which is located on what is considered a non-creeping segment of the San Andreas fault. This site shows little or no creep prior to 1998, but evidence of slow creep (1.2 mm/yr) since 1998.

Hayward fault: The northern part of the Hayward fault (H1–H3 on Fig. 3A) continues to show creep rates ranging from 3.6–5.0 mm/yr. The southern part of the Hayward fault shows somewhat higher rates, ranging from 4.4–6.4 mm/yr (H5–H10 on Figs. 3B–3C). H4 (Fig. 3A) is located near the boundary between the northern and southern segments of the Hayward fault, and continues to show the lowest creep rate (2.8 mm/yr) of our sites on the fault. Several of the central sites show increasing creep rates. H7 and H8 (Fig. 3B) appear to show a small rate of increase since 1993. The two southernmost sites at Fremont (H9 and H10; Fig. 3C) ceased creeping for 6 years after the Loma Prieta earthquake, and then resumed creeping at a rate similar to the other Hayward fault sites. Creep rate at H9 may have increased slightly since 2003 (Fig. 3C).

Calaveras fault: Our sites on the Calaveras fault show mostly unchanging creep patterns for the past few years. Creep rates are highly variable between sites, ranging from 1.0–17.6 mm/yr (Fig. 4A). Creep at the northernmost site (CV1 in San Ramon; Fig. 4A) initiated in 1992. Creep rate at this site has averaged about 3.0 mm/yr since 1992 but has apparently slowed to about 1.0 mm/yr since 2001. CV3 (Fig. 4A) continues to be our fastest creeping fault, with an average rate of 17.6 mm/yr since 1968. CV3 may have slowed slightly since 1997, but the higher creep rate before 1997 is based on just a few measurements that were collected between 1968 and 1997 by others outside of our project. As with the southern section of the Hayward fault, creep rates on the southern section of the Calaveras fault slowed after the Loma Prieta earthquake, but returned to an apparently normal rate after 5–6 years (CV4 and CV5 on Fig. 4B). Since 1996, CV5 has developed a distinct pattern of episodic creep with intervals of no creep or very low creep rates between creep episodes (Fig. 4B).

Concord-Green Valley fault: The Concord-Green Valley sites (C1–C2, GV1) continue to show consistent creep rates of 2.8–3.9 mm/yr (Fig. 5). GV1 exhibits significant site noise, probably due to seasonal effects. This site was reconfigured in 1999 for logistical reasons, after which it began to show an even higher level of noise. We recently reconfigured the site again, and the preliminary measurements now seem to show a stronger (i.e., less noisy) creep signal. Creep at both sites on the Concord fault continues to show episodic behavior with a 3–5 yr intervals between creep events. A 7-9 mm creep event occurred in late 2003. This event marks the shortest interval yet recorded between creep events (~3 yrs) at these sites (Fig. 5).

Maacama fault: Our sites on the Maacama fault continue to show creep rates of 4.6–6.5 mm/yr (Fig. 6). The creep rate at the site in Ukiah (M2 on Fig. 6) has slowed slightly since 2002 and we are watching this fault carefully for any further indications of unusual behavior.

Rodgers Creek fault: We now have several years of readings from our new sites on the Rodgers Creek fault (Fig. 6). Our eleven readings over the past two years at the Santa Rosa site (RC1 on Fig. 6) show a consistent creep rate of 3.6 mm/yr. Our other new site on the Rodgers Creek fault at Sonoma Mountain Road in Petaluma (RC2 on Fig. 6) was reconfigured after it seemed we were measuring downslope soil creep rather than fault creep. Our first measurements at the reconfigured site suggest rapid creep but after only 4 readings, the results are highly preliminary.

San Gregorio-Seal Cove fault: Sites on the San Gregorio-Seal Cove fault continue to have rather noisy signals, but consistent trends. The SG1 site on the Seal Cove fault (Princeton; Fig. 7) continues to show no indication of creep. However, readings at the SG2 site on the San Gregorio fault (Pescadero Road; Fig. 7) seem to indicate a creep rate of 5.8 mm/yr since 2002, compared to a rate of 0.6 mm/yr prior to 2002. We are watching this site carefully, particularly as there appears to be a slight acceleration on the nearby San Andreas fault (Woodside site SA4; Fig. 2A).

PROPOSED NEW ALINEMENT ARRAY SITES

We are looking into the feasibility of establishing two new sites this upcoming year. One would be a locality on the Sargent fault, and another would be a second site on the Green Valley fault.

DATA DISSEMINATION

In addition to disseminating our fault creep data via reports to NEHRP, we have also created a web site with information about fault creep, a map of our measurement sites, and a page for each site with pertinent information and creep rate graphs. We will continue to maintain and update this site each year as we collect additional data.

CONCLUSIONS

Readings from most sites continue to show consistent patterns of creep, ranging from no creep on the northern San Andreas fault to a maximum of 17.6 mm/yr on the southern Calaveras fault. Any changes to the observed creep rates must be evaluated carefully, to be certain that measurements are indicating fault creep rather than seasonal effects, soil creep, or other non-tectonic signals. We now have sufficient data to suggest that several observed changes are due to creep that may be significant.

1. Northern Calaveras fault (CV1 on Fig. 4A): deceleration of creep rate since 2002 (3.5 mm/yr before 2001; 1.0 mm/yr since 2001)
2. Rodgers Creek fault (RC1 on Fig. 6): clear evidence of the first reported right-lateral creep on this fault. Movement has been consistent since we established the site in 2002 (3.6 mm/yr); second site RC2 (Fig. 6) remains preliminary
3. San Gregorio fault (SG2 on Fig. 7): after no indication of creep from 1982–2002, an apparent increase since 2002 of 5.8 mm/yr.

REFERENCES CITED

Galehouse, J.S., 2002, Data from Theodolite Measurements of Creep Rates on San Francisco Bay Region Faults, California: 1979–2001: U.S. Geological Survey Open-File Report 02–225 (on line report) http://geopubs.wr.usgs.gov/open-file/of02-225/

Galehouse, J.S., and Lienkaemper, J.J., 2003, Inferences drawn from two decades of alinement array measurements of creep on faults in the San Francisco Bay region: Bulletin of the Seismological Society of America.

Galehouse, J.S., Brown, B.D., Peirce, B., and Thordsen, J.J., 1982, Changes in movement rates on certain east bay faults: California Division of Mines and Geology Special Publication 62, p. 236-250.

NON-TECHNICAL SUMMARY

We are measuring the rate of aseismic slip (i.e., creep) at 30 sites that cross faults in the seismically active San Francisco Bay region. Our primary purpose is to determine the rates of present fault movement and to discover any changes that might occur before, during, or after a seismic event. Potentially significant changes observed during the past year are a decreased rate on the northern Calaveras fault, an increased rate on the San Gregorio fault, and an apparently consistent rate of 3.6 mm/yr on the Rodgers Creek fault, the first reported evidence for creep on this fault.

DATA AVAILABILITY

Creep data collected from all of our sites between 1979 and 2001 are available online in Open-File Report 02-225 (http://geopubs.wr.usgs.gov/open-file/of02-225/) and in the 2001 NEHRP Final Technical Report (http://erp-web.er.usgs.gov/reports/annsum/vol42/nc/g0084.htm)

The Open-file Report contains data sheets for each site along the fault that are available for downloading in Excel format to facilitate analysis of the data. They are also available as tab-delimited raw data.

Data collected through are available on the project web site: http://virga.sfsu.edu/creep/

For additional information about our creep data, please contact either Karen Grove, 415-338-2617, kgrove@sfsu.edu; John Caskey, 415-405-0353, caskey@sfsu.edu; or Forrest McFarland (Project Manager for day-to-day operations), fltcreep@sfsu.edu.

Table 1. San Francisco State University Theodolite Measurement Sites

Fault (# on Figs.2-7)	Location (# on Fig. 1)	First Measurement	Fault Width Span (m)
San Andreas (SA1)	Alder Creek in Point Arena area (#18)	1981.025	267.4
San Andreas (SA2)	Olema at Point Reyes National Seashore (#14)	1985.096	70.6
San Andreas (SA3)	Duhallow Way in South San Francisco (#10)	1980.227	205.8
San Andreas (SA4)	Roberta Drive in Woodside (#22)	1989.844	91.2
San Andreas (SA5)	Searle Rd., San Juan Bautista (#37)	2002.799	262.7
San Andreas[1]	Pajaro Gap at Aromas (#38)	2002.107	236.3
San Andreas (SA6)[2]	Cannon Road near San Juan Bautista (#23)	1989.882	88.0
San Andreas (SA7)	Mission Vineyard Rd, San Juan Bautista (#25)	1990.553	134.2
Hayward (H1)	Contra Costa College in San Pablo (#17)	1980.609	106.8
Hayward (H2)	Thors Bay Road in El Cerrito (#34)	1989.748	120.0
Hayward[3]	Florida Avenue in Berkeley (#30)	1993.112	73.6
Hayward (H3)	LaSalle Avenue in Oakland (#29)	1993.112	182.5
Hayward (H4)	Encina Way in Oakland (#28)	1993.058	105.4
Hayward (H5)	Rose Street in Hayward (#13)	1980.481	153.9
Hayward (H6)	D Street in Hayward (#12)	1980.478	136.2
Hayward (H7)	Appian Way in Union City (#2)	1979.729	125.2
Hayward (H8)	Rockett Drive in Fremont (#1)	1979.726	180.0
Hayward (H9)	Camellia Drive in Fremont (#24)	1990.115	88.6
Hayward (H10)	Parkmeadow Drive in Fremont (#27)	1992.262	157.4
Calaveras (CV1)	Corey Place in San Ramon (#19)	1980.896	111.1
Calaveras (CV2)	Welsh Creek Road and Calaveras Road (#32)	1997.066	164.1
Calaveras (CV3)	Coyote Ranch near Coyote Lake (#33)	1972.570	101.3
Calaveras (CV4)	Wright Road near Hollister (#6)	1979.805	103.4
Calaveras (CV5)	Seventh Street in Hollister (#4)	1979.745	89.7
Concord (C1)	Salvio Street in Concord (#5)	1979.748	57.1
Concord (C2)	Ashbury Drive in Concord (#3)	1979.742	130.0
Green Valley (GV1)	Watt Drive in Cordelia (#20)	1984.456	335.8
Maacama (M1)	West Commercial Avenue in Willits (#26)	1991.871	126.1
Maacama	Sanford Ranch Road near Ukiah (#31)	1993.389	263.2
Rogers Creek (RC1)	Solano Dr. in Santa Rosa (#36)	2002.628	90.5
Rogers Creek (RC2)	Sonoma Mt. Rd., in Petaluma (#35)	2002.628	99.4
Rodgers Creek[4]	Nielson Road in Santa Rosa (#16)	1980.628	209.1
Rodgers Creek[5]	Roberts Road near Penngrove (#21)	1986.721	198.7
Seal Cove (SG1)	West Point Avenue in Princeton (#7)	1979.858	266.6
San Gregorio (SG2)	Pescadero Road near Pescadero (#8)	1982.384	455.0
Antioch[6]	Deer Valley Road near Antioch (#9)	1982.890	226.2
Antioch[7]	Worrell Road in Antioch (#11)	1980.342	103.9
West Napa[8]	Linda Vista Avenue in Napa (#15)	1980.568	130.9

[1]Site abandoned soon after established for safety reasons.
[2]Site abandoned for logistical reasons. Last measurement 1998.123.
[3]Replaced by H2 as regular measurement site.
[4]Site abandoned for logistical reasons. Last measurement 1986.055.
[5]Site abandoned for logistical reasons.
[6]Site abandoned for logistical reasons. Last measurement 1990.499.
[7]Site abandoned for logistical reasons. Last measurement 2000.158.
[8]Site abandoned for logistical reasons. Last measurement 1999.044.

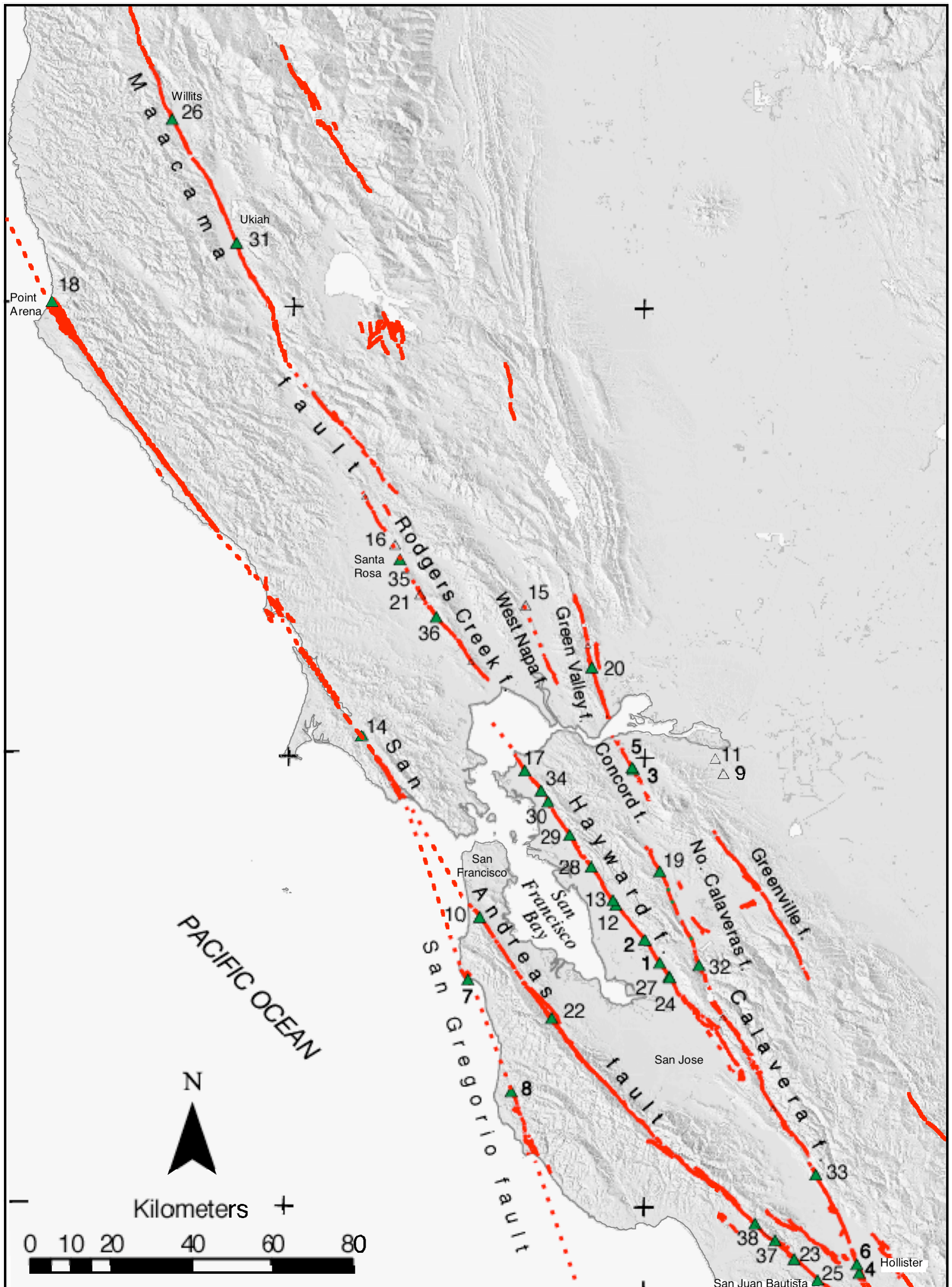


Figure 1. Numbered triangles are San Francisco State University theodolite and total-station creep measurement sites on active Bay Region faults.

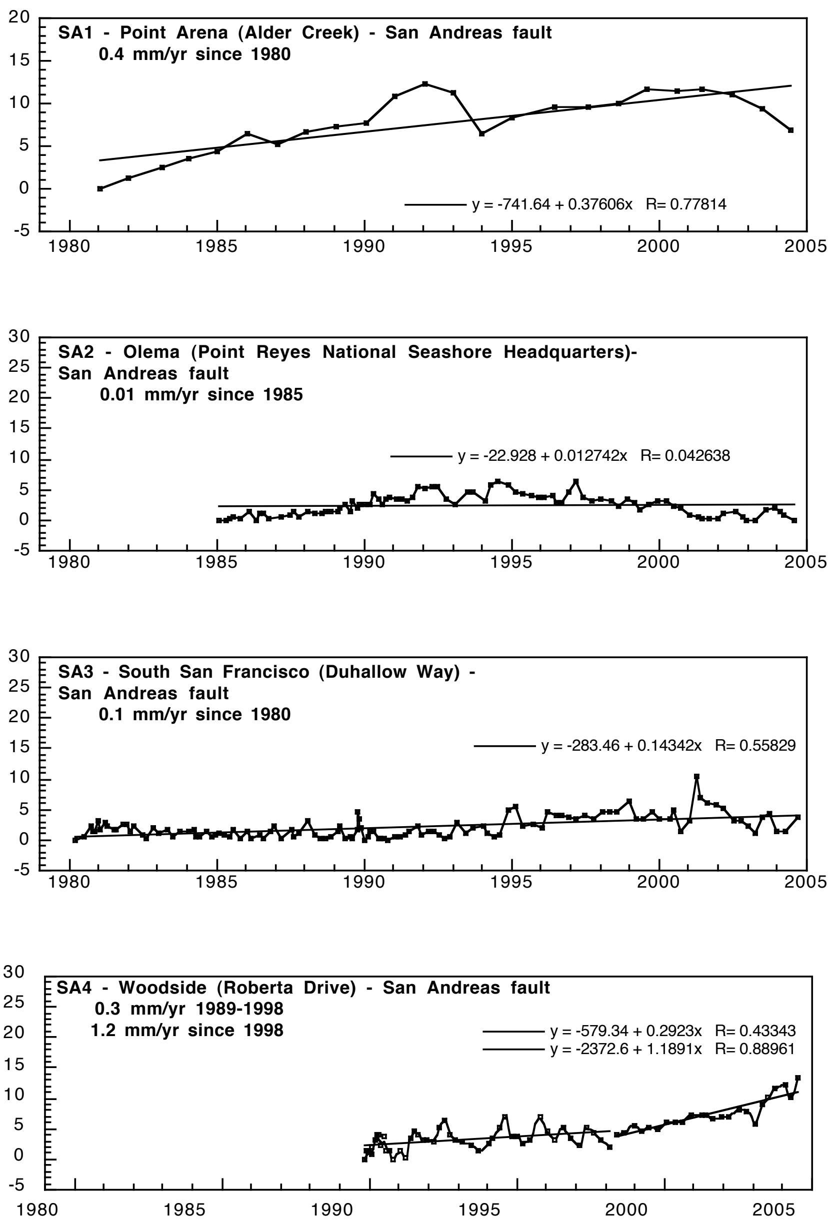


Figure 2A. San Andreas fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

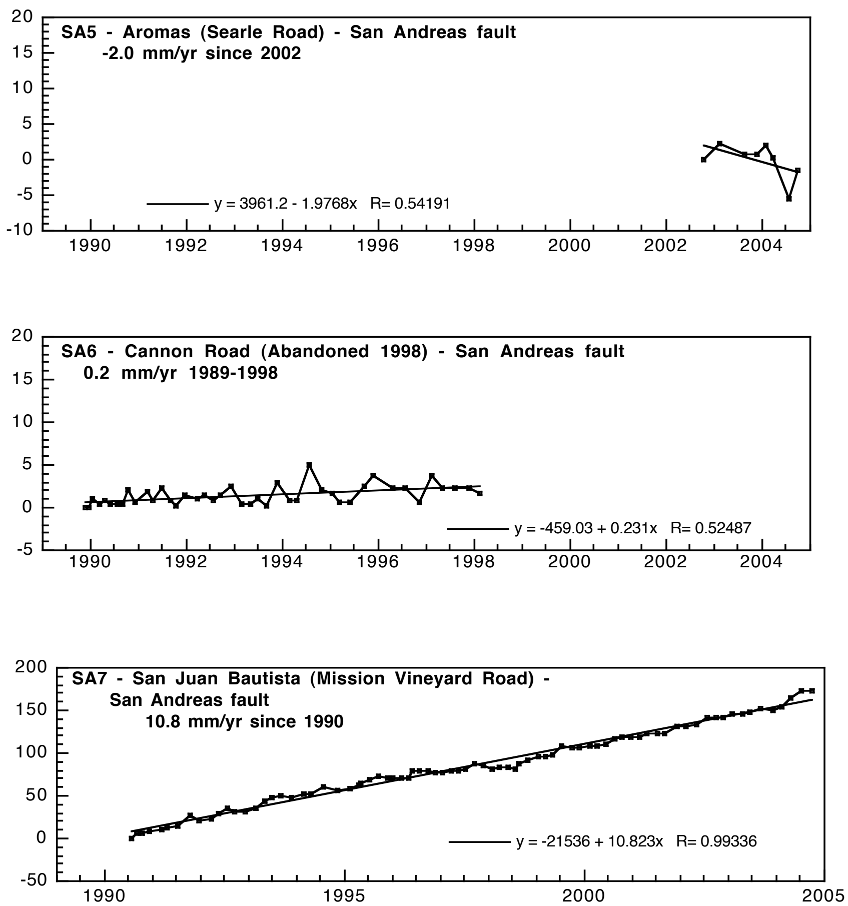


Figure 2B. San Andreas fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note change in vertical scale for SA7.

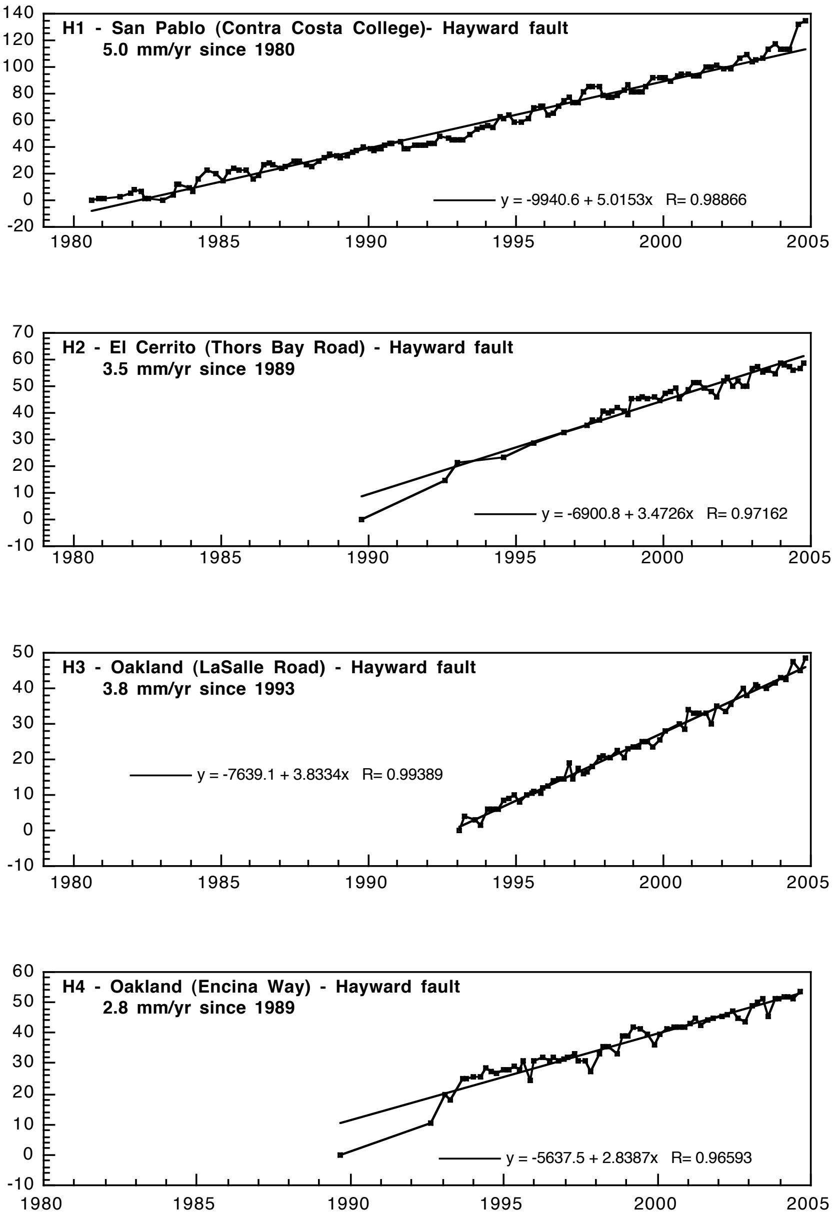
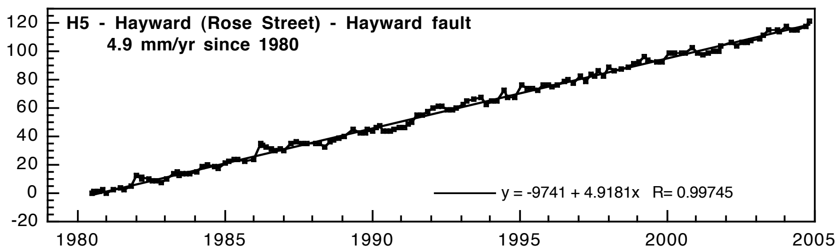
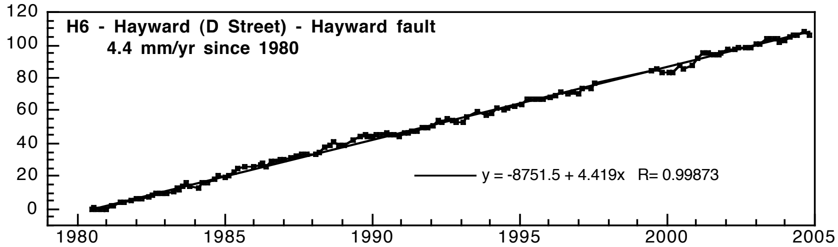
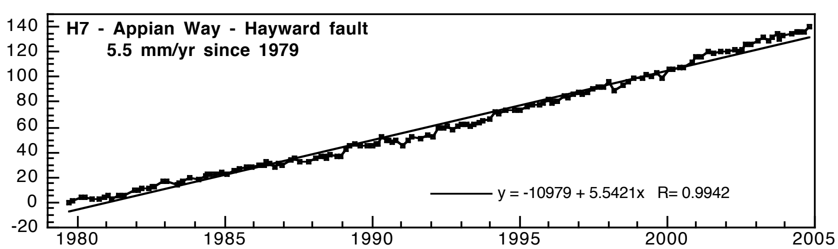


Figure 3A. Hayward fault north surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.







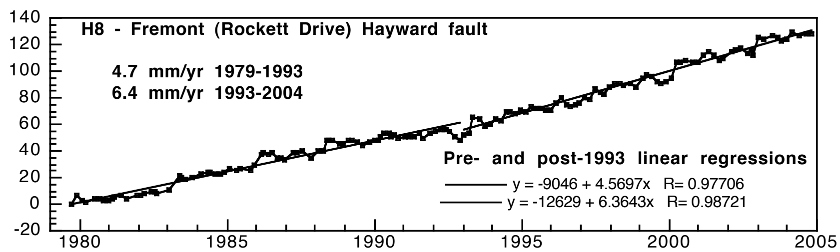
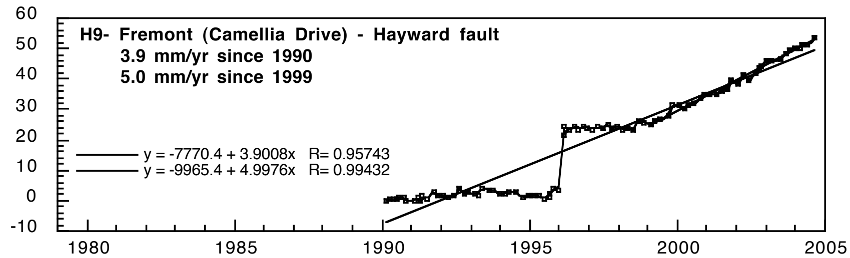


Figure 3B. Hayward fault south surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.



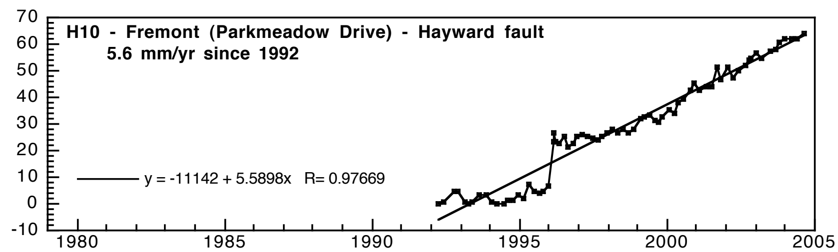


Figure 3C. Hayward fault south surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

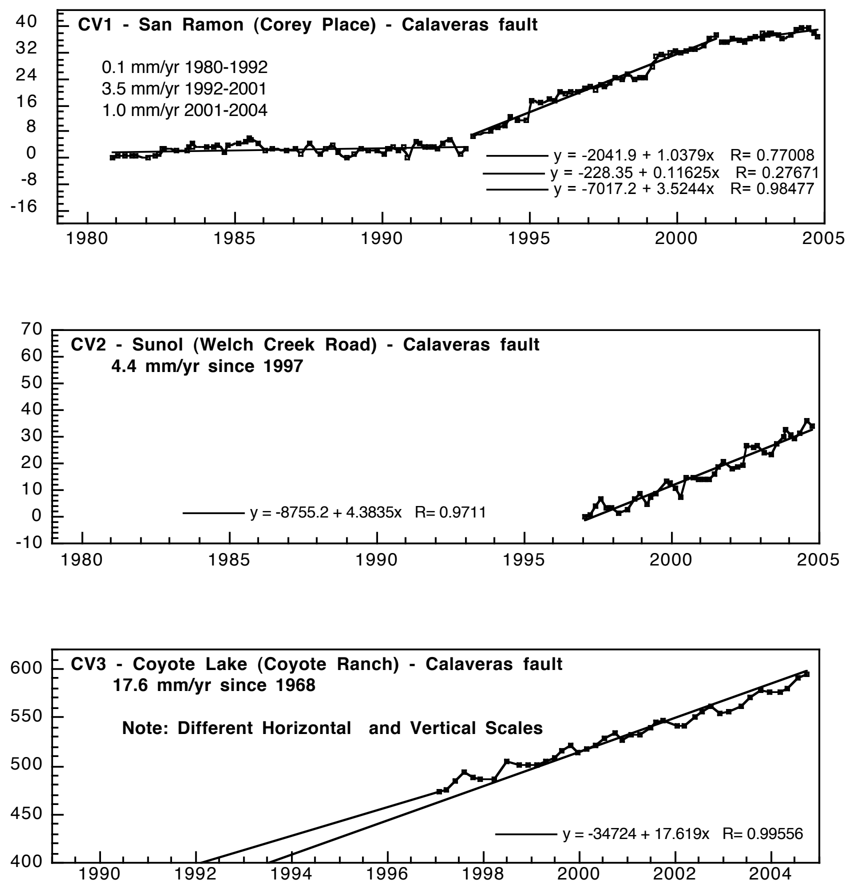


Figure 4A. Calveras fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

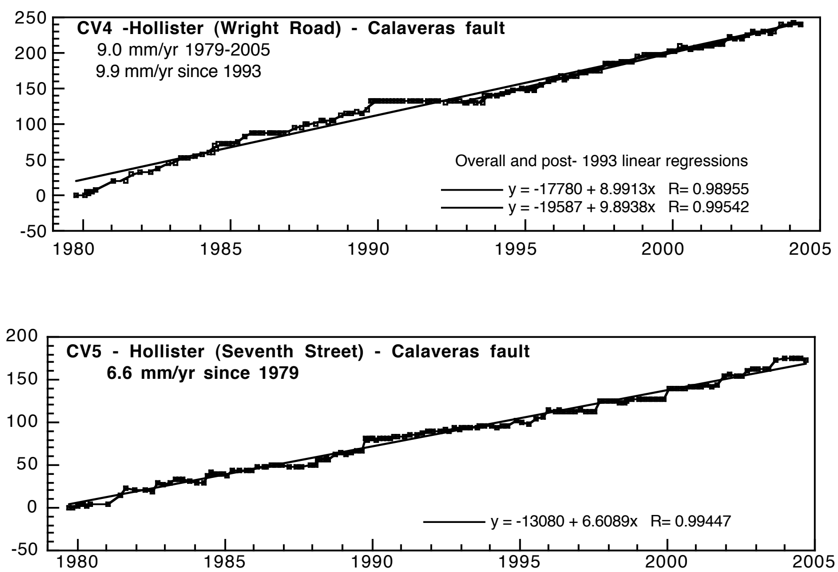


Figure 4B. Calveras fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

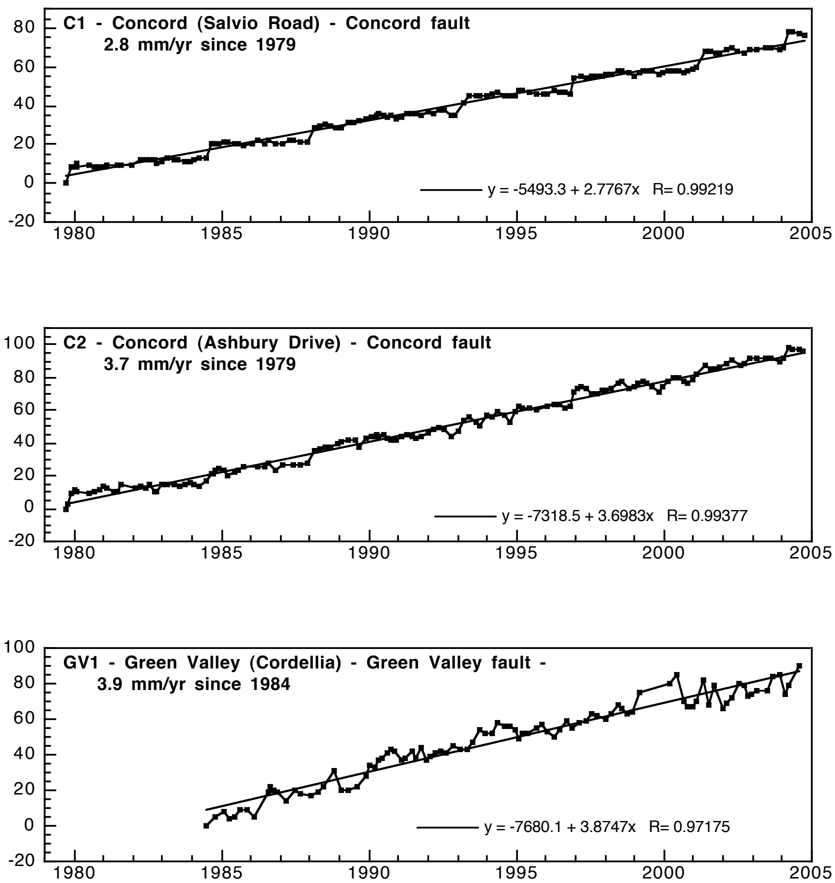


Figure 5. Concord–Green Valley fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

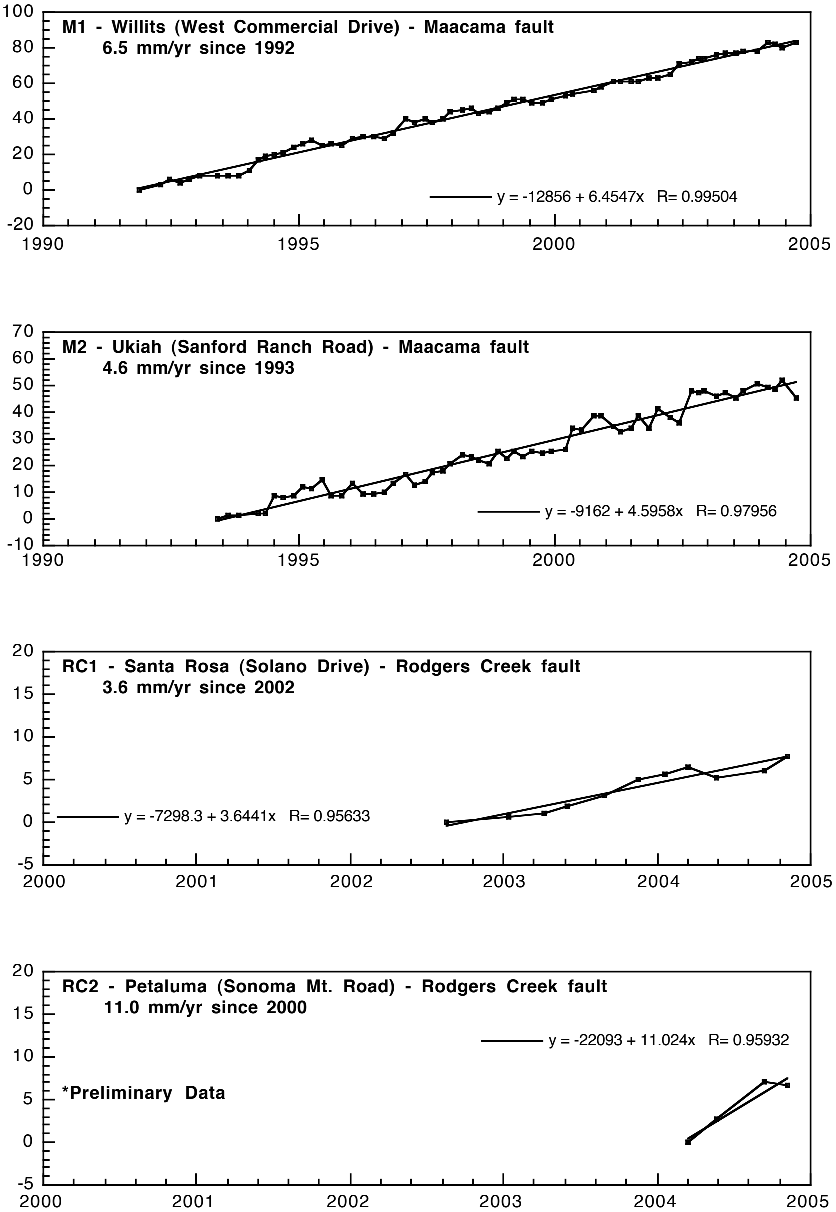


Figure 6. Maacama and Rodgers Creek faults surface displacement from 1990–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

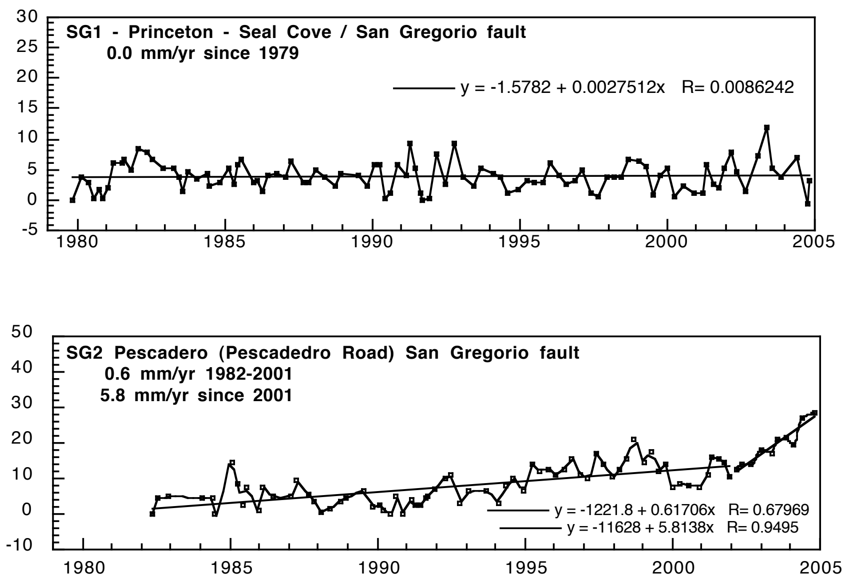


Figure 7. Seal Cove–San Gregorio fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.